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THE DETONATION BEHAVIOR OF AMMONIUM PERCHLORATE AS A FUNCTION OF CHARGE DENSITY AND DIAMETER

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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THE DETONATION BEHAVIOR OF AMMONIUM PERCHLORATE AS A FUNCTION OF CHARGE DENSITY AND DIAMETER

By

A. R. Clairmont, Jr., I. Jaffe, and D. Price

ABSTRACT: The detonability limits (critical diameter and critical density) and the dependence of the detonation velocity on density (ρ_o) and diameter (d) were studied for a finely ground ammonium perchlorate. The present data indicate that the ideal detonation velocity is D_i (mm/μsec) = -0.016 + 3.784 ρ_o (± 0.10 mm/μsec) for the range $0.6 \leq \rho_o \leq 1.26$ g/cc. The typical finite diameter curve shows that the detonation velocity is non-linear in density and exhibits a maximum in detonation velocity. The failure curve shows a monotonic increase in critical diameter with critical density in the range ρ_o : 1.0 g/cc and is opposite in trend to that for TNT. There is some indication that at high porosities (TMD ~ 30 to 50%) ammonium perchlorate and TNT exhibit the same trends.

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THE DETONATION BEHAVIOR OF AMMONIUM PERCHLORATE AS A FUNCTION OF CHARGE DENSITY AND DIAMETER

This work was carried out under ORDTASK 033 102 F009 06 01 and is part of a continuing program on the systematic investigation of the explosive behavior of composite propellant models.

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Commander

Albert Lightbody
ALBERT LIGHTBODY
By direction

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THE DETONATION BEHAVIOR OF AMMONIUM PERCHLORATE AS A FUNCTION OF CHARGE DENSITY AND DIAMETER

A. R. Clairmont, Jr., I. Jaffe, and D. Price

INTRODUCTION

Ammonium perchlorate (AP) is a high explosive, an inorganic oxidizer, and one of the most common components of composite propellants. There is very little quantitative information about the explosive behavior of composite oxidizer/fuel mixtures, and available detonation theory, based on the concept of unimolecular decomposition of pure high explosive (H.E.), cannot be expected to be applicable without some modifications. For these reasons, we have initiated a systematic study of models of a composite propellant. The investigation will be of shock sensitivity, detonability and detonation behavior as a function of physical conditions (charge diameter, density, and particle size) and of chemical composition (AP, AP/Wax, AP/Al, etc.). This report is the first on this continuing work, and presents the results obtained from an AP system of relatively small sized particles.

Aside from its importance as a major propellant ingredient, AP is in itself a very interesting H.E. It has been studied before, chiefly by Andersen and Pesante[1], but their investigation did not extend sufficiently far into the high density region to demonstrate the distinctive explosive behavior defined by the present results. These show that AP provides a classic example of a group of explosives which exhibit more ideal behavior at high porosity as opposed to conventional H.E.'s which behave more ideally at low porosity (see ref. 2).

EXPERIMENTAL

The ammonium perchlorate, NH_4ClO_4, Lot No. XP-17, was supplied by Thiokol Chemical Company. It conformed to the Navy Department specifications for AP[3] with the exception that it contained 1% tricalcium phosphate instead of the specified 0.1 - 0.2%. The phosphate is an anti-caking agent and was used in a higher than usual concentration because this AP was finer than usual. By Micromerograph (see Fig. 1) its average particle size was 10 μ.

The AP was dried in a 50°C oven for at least four hours before being used to prepare charges. The charges were fired as soon as possible after preparation; they were stored in a 30°C oven prior to firing and exposed to the atmosphere 45 minutes or less while being mounted for firing.

Cylindrical granular charges were prepared with diameters of 1.90 to 7.62 cm and a length of 20.32 cm. The lowest density charges ($\rho_o \leq 1.0$ g/cc) were hand packed and pressed in 0.08 mm thick cellulose acetate envelopes. At $1.0 < \rho_o \leq 1.2$ g/cc, charges were prepared in two increments on the hydraulic press. For $\rho_o >$ 1.2 g/cc, the AP was compacted in the isostatic press, after which the charge was machined to size.

The average bulk density of the charge could be determined very accurately, to within 0.2% in the worst case. There was, however, no check on the uniformity of the density within the charge except by visual inspection and rejection of faulty charges. Charges prepared isostatically should be the most uniform, and they appeared to be excellent. In the density range of 1.0 to 1.2 g/cc, charges of good uniformity could be obtained with careful preparation and handling. In particular, at $\rho_o \leq 1.0$ g/cc, the charge must be fired within a day after its preparation. If it is allowed to stand longer, aging and settling will produce small cracks and even

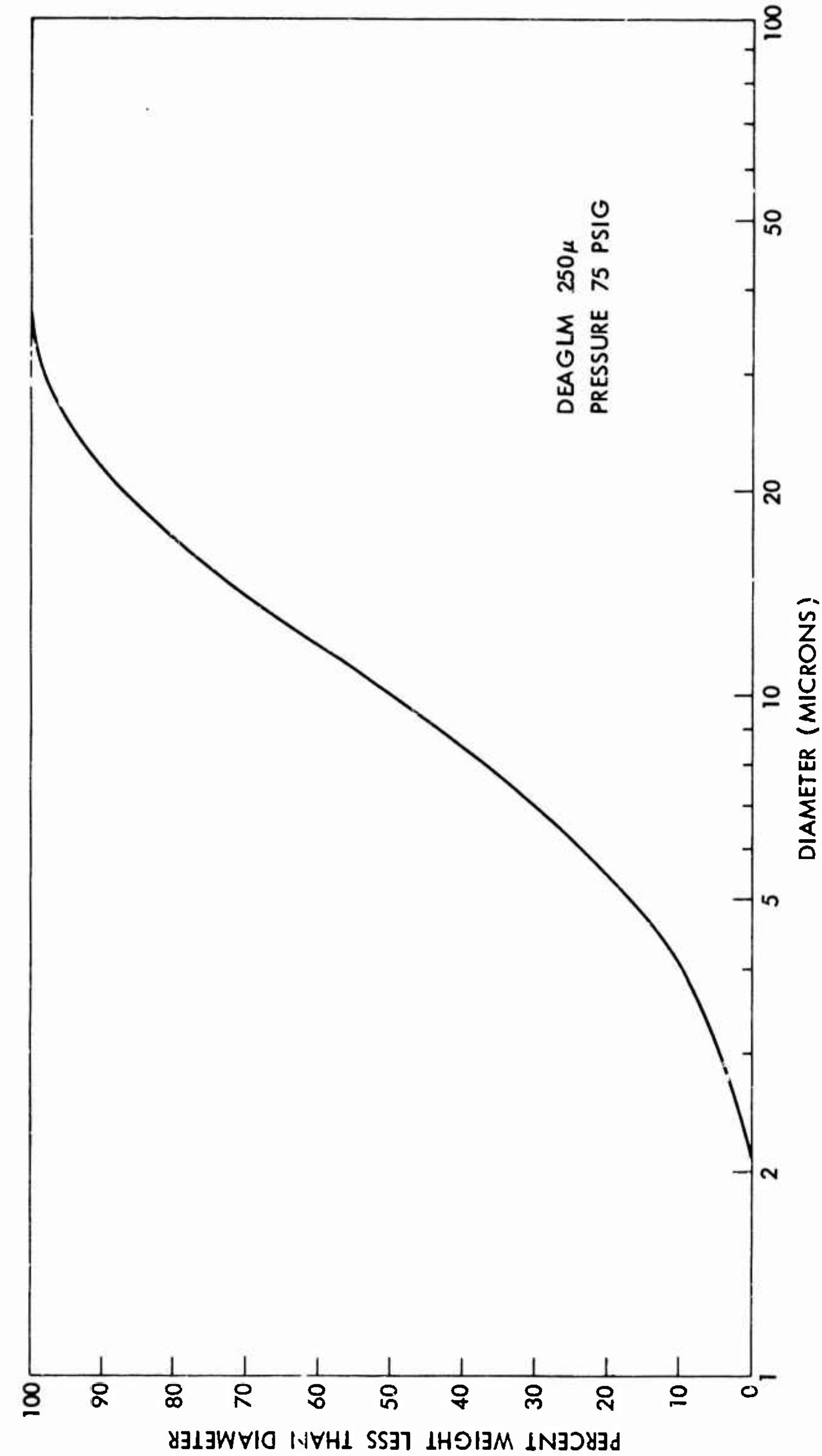

FIG. 1 PARTICLE SIZE DISTRIBUTION OF AP (10μ)

column separation in such a very low strength charge. Charges of $\rho_o < 1.0$ were only fair in uniformity even with careful preparation and no aging. The hand-sifted preparation ($\rho_o \sim 0.6$ g/cc) was the most uniform of these and the intermediate range $0.6 < \rho_o < 1.0$, contain the least satisfactory charges.

The AP charges were used in the experimental set-up of Fig. 2. Boosters were either tetryl (ρ_o = 1.51 g/cc) or pentolite (ρ_o = 1.56 g/cc) initiated by an Engineer's Special detonator. Each AP charge was capped by a witness charge of the same H.E. as the booster.

A 70 mm smear camera was used to follow the reaction front in the AP charges. The camera slit was focused on the charge's periphery and was parallel to its longitudinal axis. The camera recorded the luminosity (or flasher-enhanced luminosity) of the detonation front. The camera speed was set between 1 and 3 mm/μsec to obtain a smear trace at approximately 45° to the base of the film. The film used was selected on the basis of expected exposure from the combination of luminosity of the front and the film speed. Table A1 of the appendix gives the conditions used for each shot.

In general, the smear record was obtained for the last 15 cm of the AP charge, but when detonation occurs, the velocity measurement can be made from the smear produced by the last few centimeters of the charge. Under these circumstances, the smear record was frequently taken only for the last 6 to 7 cm of the charge to utilize the higher resolution of higher writing speed. The length of charge observed and camera writing speed are also listed in Table A1.

RESULTS

The smear camera records were read directly on the Universal Telereader and simultaneously punched on the IBM cards by the Telecordex. For a camera speed of 1 to 3 mm/μsec, the time can be

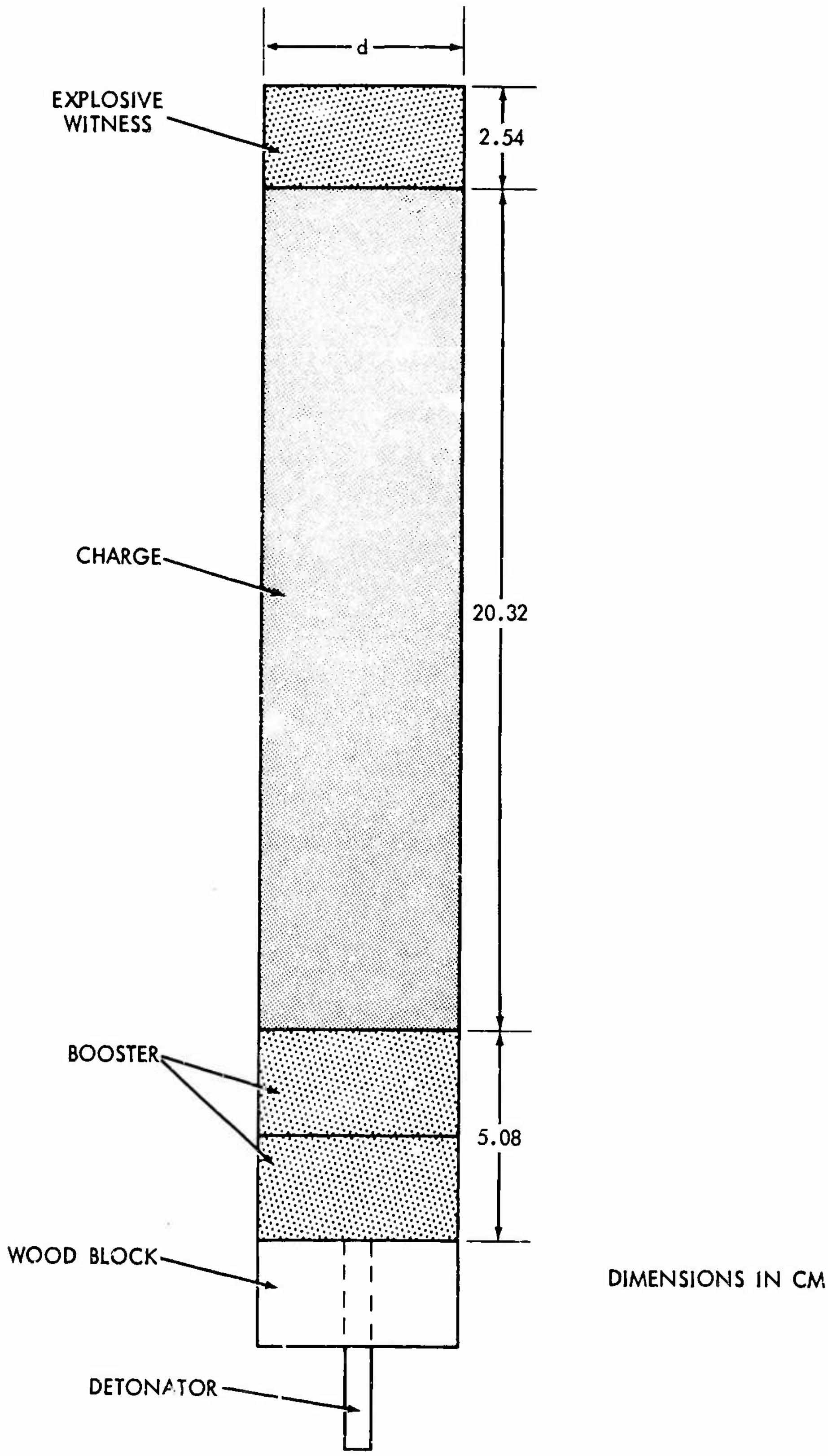

FIG. 2 EXPERIMENTAL ASSEMBLY

read to 0.03 to 0.01 μsec. For a charge length of 20 to 7 cm, the distance can be read to 0.11 to 0.04 mm. When detonation occurred, the time-distance data, on punch cards, were fitted by least squares to a straight line by a program for the 7090. Error in the determined velocity from errors in record reading is estimated, in the worst case, to be 1.5%.

Table 1 contains nearly all the data collected. Among them are nine replications: seven pairs and two groups of three. The average deviation per shot ranges from 0 to 1.4% of the measured detonation velocity with the distribution: 0.0 - 0.1% (4), 0.3 - 0.7% (4) and 1.4% (1). For the region covered by these data, that for which $\rho_o \geq 1.0$ g/cc, the over-all experimental precision is also 1.5% or less.

Typical records are shown in Figs. 3 - 5 where time increases from left to right. Fig. 3 (Shot 93) is of a charge which detonated. At the left of the figure is a still picture of the original charge and its explosive witness pellet. The region observed by the smear camera is along the bright axial line which is bracketed by the two dark inked lines. To the right of the still, the slit is reproduced again (vertical lines) as well as a line approximately perpendicular to it. These lines provide fiducial marks to permit obtaining the appropriate charge location corresponding to each point on the smear trace. They also assist in reading the record on the Telereader.

The initial bright portion of the smear and the curvature of that part of the trace results from overboostering combined with the effect of a curved initiating front. After a run of 2.5 cm (less than the charge diameter) the trace becomes straight and remains so until the end of the charge where the witness detonates.

Fig. 4 (Shot 69) is an example of a smear record of a charge which is just sub-critical. The trace is curved and fading, but

TABLE 1

DETONATION VELOCITY VS DENSITY FOR AP (10 μ)* AT VARIOUS DIAMETERS

Shot No.	ρ_o	D	Reaction Quenched at δ cm	Reaction Quenched at δ d	Front Velocity at End of Record mm/μsec	Comment
Diameter = 1.90 cm; (ℓ/d) = 10.7						
137	0.70	F**	2.05	1.08	1.58	
147	0.80	F			1.53	Extra booster used
173	0.90	F	7.0	3.7	1.63	
174	1.10	F	7.0	3.7	1.92	
Diameter = 2.22 cm; (ℓ/d) = 9.2						
153	0.60	F	10.6	4.8	1.32	
149	0.60	F	-	-	-	
141	0.62	1.55	-	-	-	
143	0.71	1.65	-	-	-	
144	0.81	1.88	-	-	-	
142	0.91	2.11	-	-	-	
148	0.96	2.21	-	-	-	
52	1.00	F	17.0	7.5	2.29	
Diameter = 2.54 cm: (ℓ/d) = 8.0						
101	0.61	1.69	-	-	-	
150	0.80	2.16	-	-	-	
124	0.90	2.49	-	-	-	

TABLE 1 (Cont'd)

Shot No.	ρ_o	D	Reaction Quenched at δ cm	Reaction Quenched at δ d	Front Velocity at End of Record mm/µsec	Comment
49	1.00	2.87	-	-	-	
55	1.00	2.85	-	-	-	
56	1.00	2.75	-	-	-	
127	1.10	2.74	-	-	-	
126	1.15	2.68	-	-	-	
139	1.20	F	11.4	4.5	2.57	
85	1.26	F	8.1	3.2	-	**AP recovered**
Diameter = 3.49 cm; (ℓ/d) = 5.8						
60	1.00	3.03	-	-	-	
61	1.00	3.07	-	-	-	
131	1.10	3.26	-	-	-	
132	1.15	3.24	-	-	-	
89	1.22	3.40	-	-	-	
87	1.22	3.37	-	-	-	
88	1.22	3.37	-	-	-	
94	1.24	3.33	-	-	-	
95	1.27	3.33	-	-	-	
98	1.28	3.33	-	-	-	
109	1.34	3.20	-	-	-	
111	1.34	3.22	-	-	-	
110	1.34	3.19	-	-	-	

TABLE 1 (Cont'd)

Shot No.	ρ_o	D	Reaction Quenched at δ cm	d	Front Velocity at End of Record mm/μsec	Comment
112	1.39	F	12.7	3.5	2.79	
Diameter = 5.08 cm; (ℓ/d) = 4.0						
136	0.61	2.04	-	-	-	
154	0.80	2.76	-	-	-	
53	0.99	3.30	-	-	-	
54	1.00	3.26	-	-	-	
70	1.26	3.85	-	-	-	
71	1.34	3.92	-	-	-	
72	1.38	3.92	-	-	-	
73	1.45	3.66	-	-	-	
74	1.45	3.66	-	-	-	
69	1.48	F	>20.3	>4.0	3.22	Just subcritical. See Fig. 4
Diameter = 7.62 cm; (ℓ/d) = 2.7						
63	1.00	3.43	-	-	-	
64	1.00	3.43	-	-	-	
91	1.22	4.04	-	-	-	
92	1.23	4.12	-	-	-	
93	1.26	4.17	-	-	-	
114	1.40	4.43	-	-	-	
116	1.41	4.43	-	-	-	

TABLE 1 (Cont'd)

Shot No.	ρ_o	D	Reaction Quenched at δ cm	d	Front Velocity at End of Record mm/µsec	Comment
113	1.45	4.44	-	-	-	
115	1.46	4.45	-	-	-	
134	1.57	F	>20.3	>2.7	3.73	Near critical
117	1.66	F	10	1.3	3.49	
118	1.67	F	-	-	-	No photographic trace

*AP has a weight mean particle size of 10.4 µ from micromerograph Fig. 1. Its cumulative weight percent on various fine screens, at a separator speed of 3500 RPM, was 0.5, 1.5, 3.1, 3.6, and 3.9 % respectively on sieves No. 100, 140, 200, 230, and 270.

**Failure

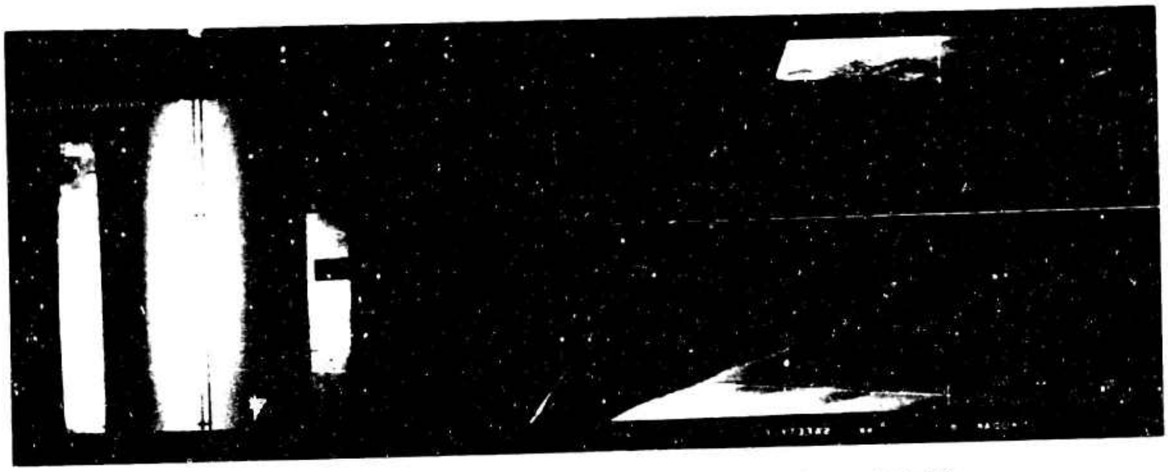

FIG. 3 SMEAR RECORD FOR SHOT [illegible]

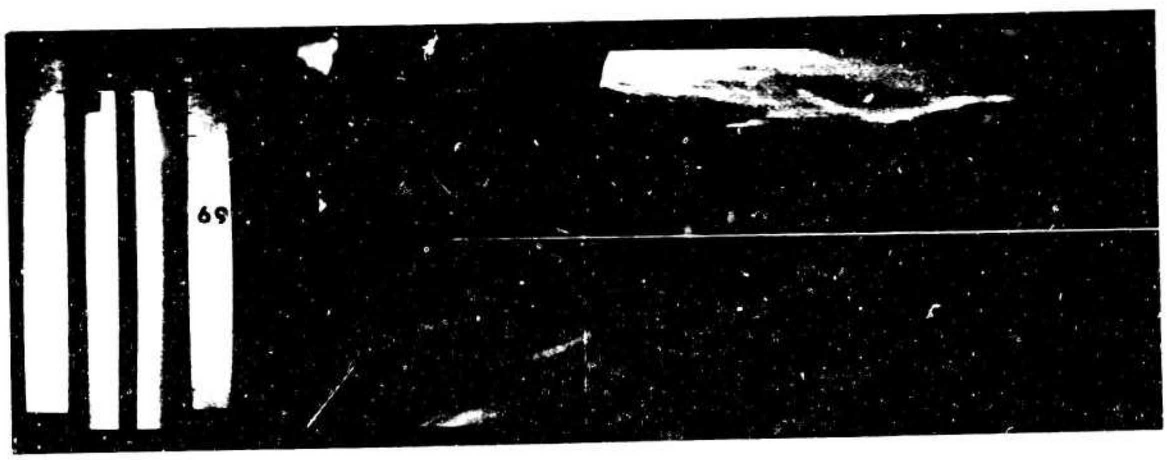

FIG. 4 SMEAR RECORD FOR SHOT 69 [illegible] REACTION, FAILURE MODERATELY SLOW

FIG. 5 [illegible]

sufficient reaction persists to initiate detonation of the witness pellet.

Fig. 5 (Shot 85) is the record from a clearly subcritical charge. A fading reaction, induced by the shock from the booster, fails after traveling about two diameters down the charge. The witness pellet at the end of the charge is not initiated.

DISCUSSION

Detonability

The data of Table 1 will be examined in a number of ways. First it is most convenient to establish the extreme behaviors, the ideal and the failure regions. Starting with the latter, we have selected from Table 1 the data which establish the limit or failure line in the charge diameter vs charge density plane. These data are listed in Table 2 and part are plotted in Fig. 6. They show the critical diameter (d_c) vs critical density (ρ_c) curve for this particular AP at an ambient temperature of about 25°C and in the range of $1.0 \leq \rho_o \leq 1.57$ g/cc.

The critical diameter is that diameter at and above which detonation propagates and below which it fails. The failure of detonation when the charge diameter is subcritical is attributed to quenching of the detonation reaction zone by the arrival of lateral rarefactions. It is, therefore, a two dimensional effect, and the critical diameter will be closely related to the reaction zone length; the two quantities will vary in the same way.

Fig. 6 shows that for AP, d_c (and hence reaction zone length) increases with increasing ρ_o (above ρ_o = 1.0 g/cc), a trend opposite to that observed in common conventional H.E. such as TNT[2]. Moreover, for a given diameter, the critical density is that <u>above</u>

TABLE 2

LIMIT DATA FOR AP (10 μ)

Diameter (cm)	Limit Density (g/cc) ρ^+	ρ^-
1.90	none	0.7 to 1.1
2.22	0.62	0.60
2.22	0.96	1.00*
2.54	1.15	1.20
3.49	1.34	1.385
5.08	1.454	1.484*
7.62	1.46	1.57*

*Judged very close to critical value.

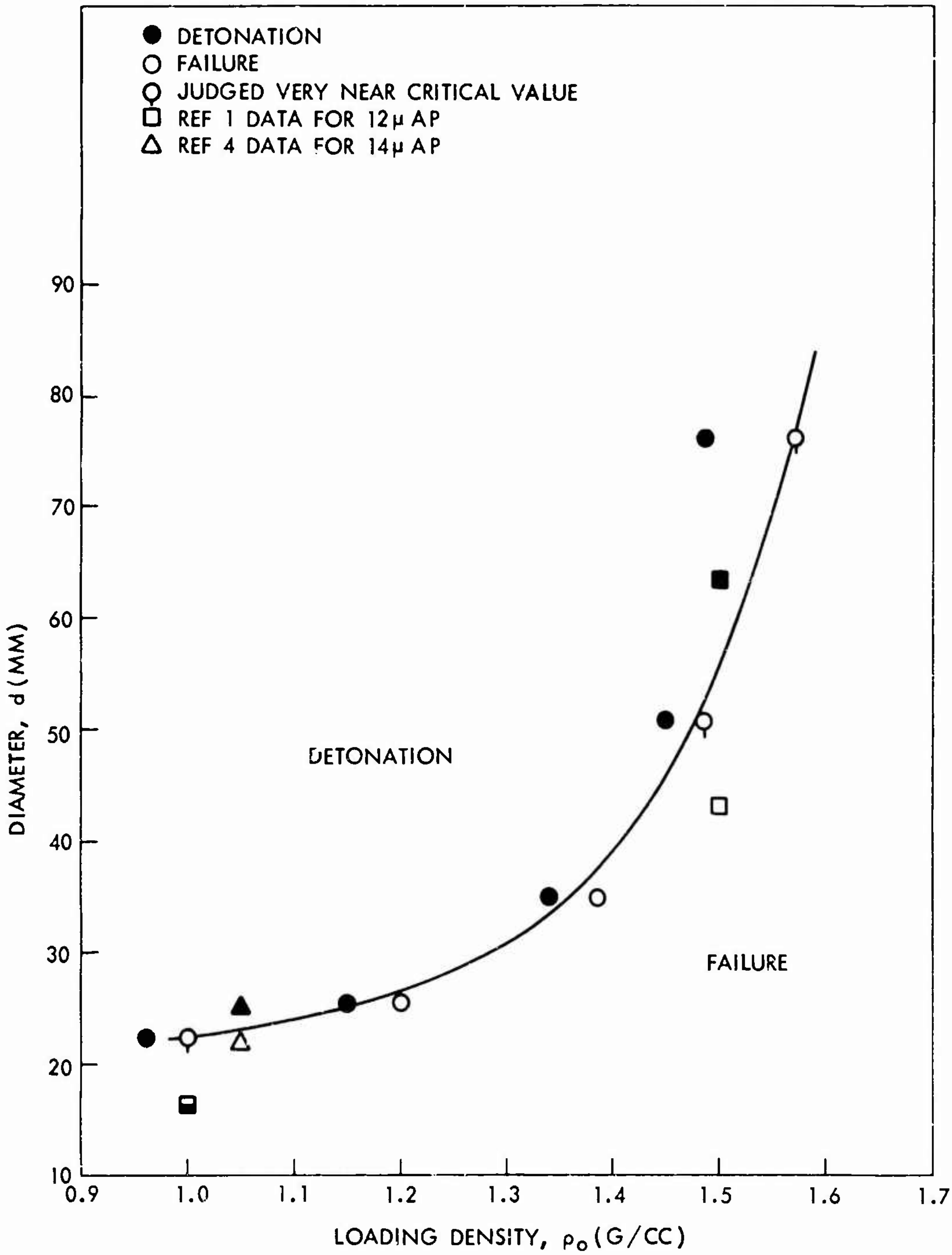

FIG. 6 DETONABILITY LIMIT CURVE FOR AP(10μ)

which detonation cannot occur. (For TNT, ρ_c is that below which detonation cannot occur.)

In addition to our own data, Fig. 6 shows other investigators' results for AP of about the same average particle size as that which we have used. The qualitative form of Fig. 6 had already been established by Anderson and Pesante[1] as their values at two densities show. The order of magnitude comparison between our results and theirs is quite satisfactory. Detailed consideration merely emphasizes that a single number such as a weight average particle size (or a surface area computed from it) cannot by itself adequately characterize a granular AP sample. Thus Ref. (1) results indicate a d_c lower than ours; Ref. (4) results, a d_c about equal ours, both at $\rho_o = 1.0$ g/cc. However, the average particle size is in both cases supposedly greater than ours and one would expect therefore greater values of d_c. (d_c decreases with particle size if the size change is caused by grinding[2].)

The form of Fig. 6 immediately suggests examining the curve ρ_c vs d_c^{-1}. When smoothed data from Fig. 6 are so plotted, the sigmoid curve of Fig. 7 is obtained; it indicates an asymptotic approach to a large value of the critical diameter at $\rho_o = 1.95$ g/cc, the crystal density of AP. But a straight line extrapolation through the point of inflection of Fig. 7 gives $\rho_c = 1.74$ at $d_c^{-1} = 0$. $d_c^{-1} = 0$ or $d_c = \infty$ means, of course, a nondetonable material, and the straight line extrapolation suggests the possibility that this AP, in charges for which $1.74 \le \rho_o \le 1.95$, is nondetonable. However, this linear extrapolation is of dubious validity since the limit curve of Fig. 6 is not sufficiently accurate and does not extend to sufficiently high values of ρ_o to justify such a treatment. The question of whether there is a critical density below the crystal density of AP for which the material is nondetonable at any diameter can only be resolved by investigating the detonability of much larger charges than can be fired in the present work.

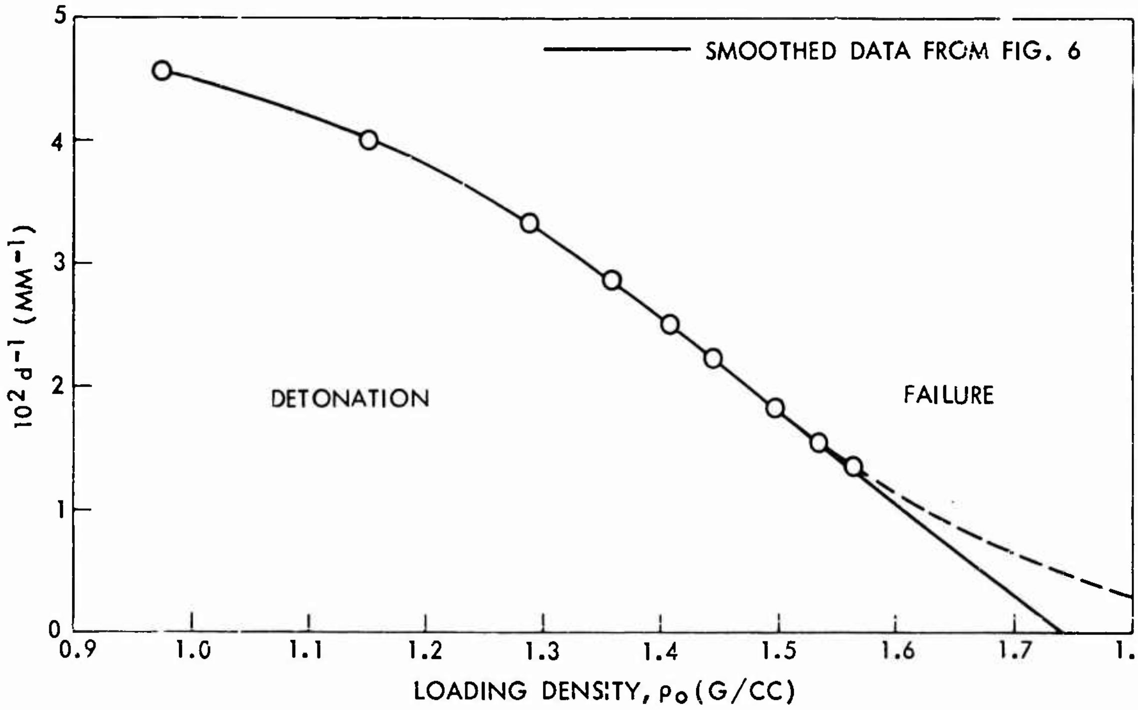

FIG. 7 DETONABILITY LIMIT CURVE FOR AP(10μ) IN FORM OF d^{-1} VS ρ_o

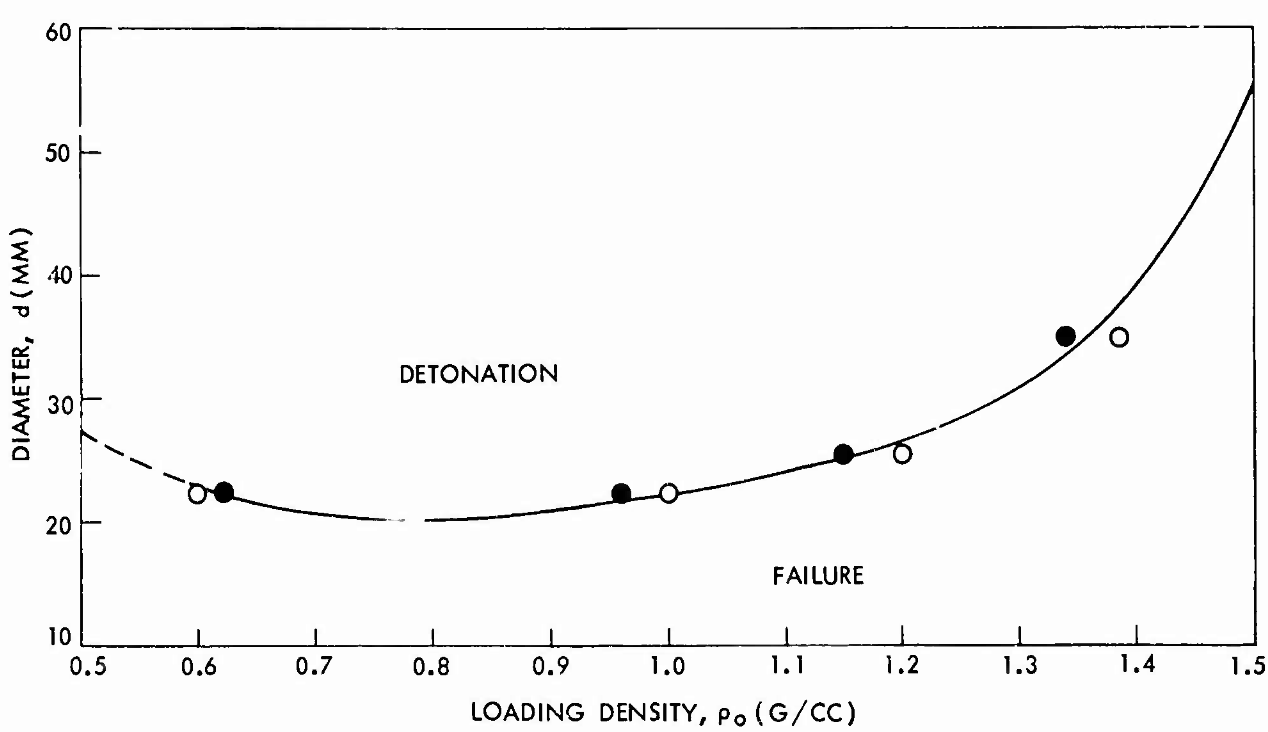

FIG. 8 POSSIBLE FORM OF LIMIT CURVE FOR AP (10μ)

Although our results cannot answer this question, they make very clear the difficulty of detonating granular AP at high loading density. The difficulty increases as the particle size of AP increases, for the limit curve of Fig. 6 shifts to larger diameters as the particle size increases[2]. This information is part of that being collected for application to problems of detonability of composite propellants where AP is present as a component in an almost voidless charge.

Fig. 6 shows the limit curve only for $\rho_o \geq 1.0$ g/cc. The data of Table 2, however, give d_c (ρ_o = 0.61) = d_c (ρ_o = 1.0) as do also the data of Ref. (1). Existence of one point on the limit curve where the critical density is double-valued suggests that the complete limit curve might be of the form of Fig. 8, and that <u>at sufficiently low densities</u> there is a second critical density value <u>below</u> which detonation cannot occur. In other words, at sufficiently low densities, the limiting behavior may be similar to that of conventional H.E. Note that in Table 2, at d = 2.22 cm, detonation occurs at 0.62 g/cc and fails at 0.60 g/cc, the lower ρ_o; whereas at $\rho_o > 0.61$, failure always occurs at the higher ρ_o. Unfortunately, it is experimentally impossible to prepare charges of this AP at densities lower than 0.60 g/cc and hence to explore this lower density region*. We will, however, look for a similar phenomenon in an experimentally accessible region in other explosives.

Another implication of Fig. 8 is the existence of a diameter below which AP (10 μ) will not detonate at any density. This diameter is the minimum on Fig. 8 and would in this case be close to 2.2 cm (see Fig. 9).

*Indeed, it is impossible to explore the region $\rho_o \sim 0.8$ g/cc more quantitatively because of the difficulty of preparing good charges. We know only that 1.90 cm < d_c (ρ_o = 0.8) < 2.22 cm.

Detonation Behavior Pattern

The D data of Table 1 are plotted as functions of ρ_o along constant d curves in Fig. 9. Typically, the nonideal charges exhibit, at a fixed diameter, a detonation velocity increasing with increasing ρ_o to a maximum value. Beyond this maximum, D decreases as ρ_o increases until it reaches its critical value at the failure limit. The limit line, dividing the detonation from the failure area ($\rho_o > 1.0$ g/cc) has been drawn through smoothed data obtained from Fig. 6. It is shown as a dashed line which gives the critical detonation velocity as a function of ρ_c and is slightly concave upward. It runs into the D vs ρ_o curve for d = 2.22 cm. This latter curve is considered an extension of the limit line since none of the charges at 1.90 cm diameter could be detonated.

At the left of the curves is a second tentative limit line for the lower densities in accord with the suggested curve of Fig. 8. It is possible, of course, that better definition in the region $\rho_o \sim 0.8$ g/cc might show the first limit curve dipping slightly below the 2.22 cm curve before it joins the second limit curve at $\rho_o \sim 0.61$ g/cc.

The curves, d > 2.22 cm were obtained by using the best visual fit $\rho_o \geq 1.0$ g/cc and a straight line in the interval of 0.6 to 1.0 g/cc. The experimental difficulty of obtaining charges in this density range is the cause of the scarcity of data here. It is also probably more to blame for the large scatter than is the assumed linear form. Certainly the two 4% deviations from the curves at $\rho_o = 0.8$ are the largest in all these data. The next largest is < 2%.

The overall detonation behavior illustrated in Fig. 9 is an approach to the infinite diameter value with increasing diameter and <u>decreasing</u> density. As ρ_o increases, D values diverge

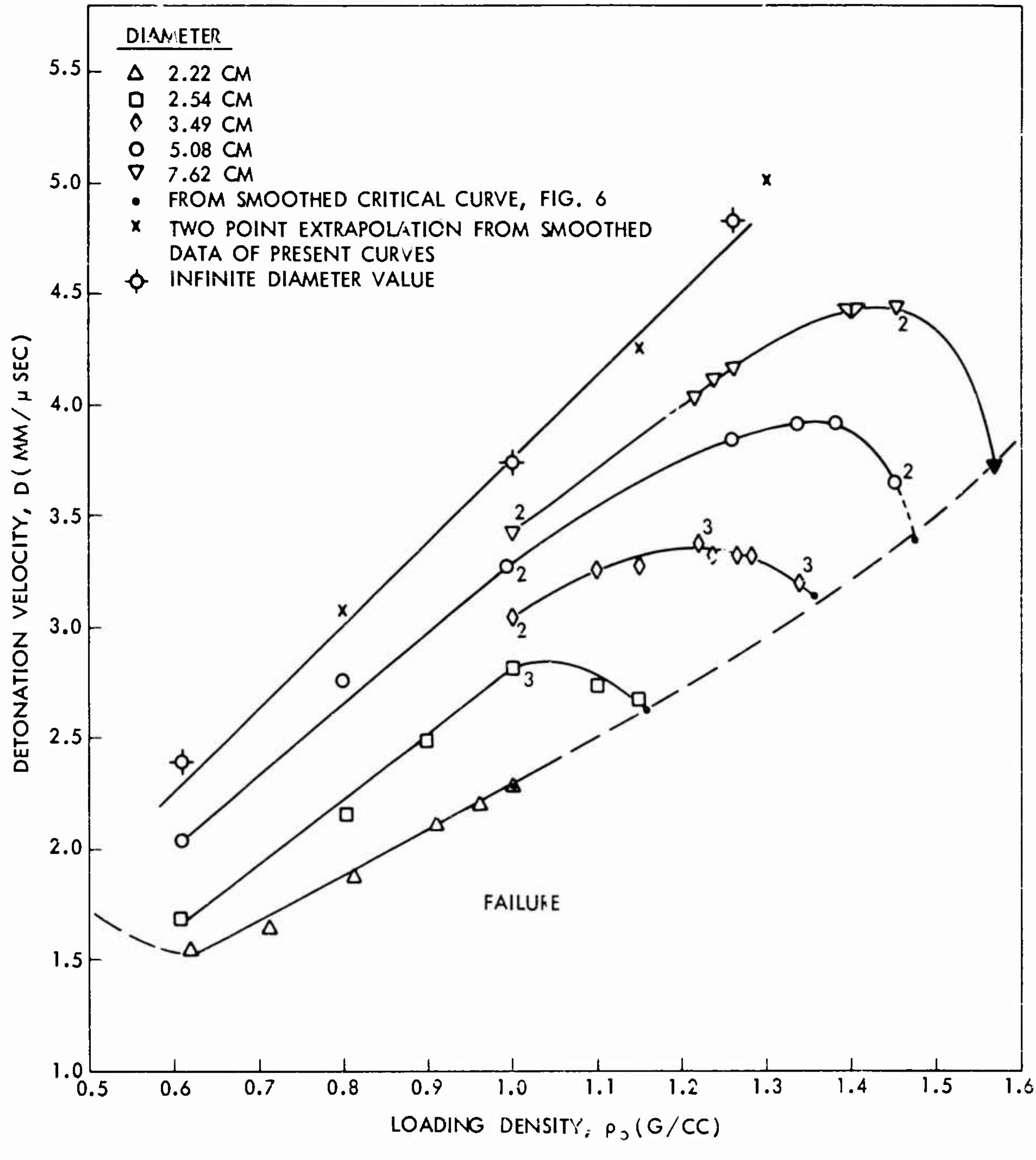

FIG. 9 THE DETONATION BEHAVIOR OF AP (10 μ)

increasingly from the ideal. This is a detailed example of the behavior expected from members of the group 2 explosive class discussed in Ref. (2). It is also opposite in trend to that shown by conventional or group 1 H.E. which approach ideal behavior as density increases.

It is of interest to note that as the critical density is just exceeded for each value of d, the shock-induced reaction fails, but nevertheless **persists** for quite an interval. Table 1 shows several failing reactions which propagate 3 - 4 diameters before fading completely. This behavior is in contrast to that of TNT-like explosives for which low porosity charges show sharp failure at the critical density.

The persistence of a fading reaction is of itself an interesting phenomenon which we plan to investigate further. Here it has practical implications in making the limit line of Fig. 6 and hence that of Fig. 9 less certain. With our charge length of 20.3 cm, the experimental range in ℓ/d is from about 10 to 2.7. The longest run for a failing reaction in Table 1 is about 7.5 d; moreover, reactions have failed after several diameters travel at what appeared a constant velocity. This situation introduces uncertainties which the data at d = 5.08 cm illustrate. Here ℓ/d = 4.0, and the records showed a constant velocity over the last half of the charge for ρ_o = 1.45 g/cc and a slightly falling one at ρ_o = 1.48 g/cc. Consequently we have shown 1.45 < ρ_c < 1.48 g/cc and placed ρ_c near 1.48 g/cc in Fig. 6. However, we also prepared a charge of ℓ/d = 8.0 by using two isostatically pressed, 20.3 cm long cylinders of ρ_o = 1.45 g/cc in tandem. The camera viewed only the last 19 cm of the charge and hence just missed the contact surface between the two cylinders. The record of this shot showed a very short, but apparently linear, trace (3.05 mm/μsec) which faded completely after 6.86 cm, i.e., at 28.4 cm (5.6 diam) from the booster end of the charge. Since ρ_o = 1.45 g/cc is certainly very close to the true

ρ_c, interruption of the charge by the use of two segments could cause such a failure. Obviously a single cylinder charge of this density and $\ell/d \sim 8$ would have to be tested to confirm or shift our present boundaries for the critical density.

The exact location of a limit curve such as Fig. 6 does not seem of great importance because it will probably differ for every batch of AP used. However it is of importance to investigate the cause of the nonlinear D vs ρ_o curves of Fig. 9. As the start of such a study, conductance* during and after detonation was measured on 5.08 cm charges. The AP at ρ_o = 1.26 g/cc (64.6% TMD) showed a maximum conductance equal that of a coarse HMX at ρ_o = 1.22 g/cc (64.2% TMD) but lasting 1.7 times as long. The maximum conductance of the AP at 1.38 g/cc and at 1.47 g/cc is the same and about 40% higher than that found at ρ_o = 1.26 g/cc. There is therefore little doubt that considerable reaction has been induced by shocking the 1.47 g/cc AP charge - and at a distance of 7.6 cm (1.5 d) from the point of entry of the shock - although it is quite probable that detonation does not occur and that the induced reaction will fade after a longer run.

Ideal Behavior

Fig. 9 shows, as its top curve, the ideal or infinite diameter curve derived from those below it. Some discussion of its derivation and form is necessary.

We have studied only one other pure explosive exhibiting nonideal curves of the form shown in Fig. 9; that material was

*This work was carried out as part of a development program for conductivity measurements. It will be reported in detail when the development work is completed.

hydrazine mononitrate (HN). Although HN was not studied in as great detail as this AP, the results for it clearly indicated that the form of the nonideal curves (and existence of a maximum) were two-dimensional effects, that at a sufficiently large diameter, a conventional linear D vs ρ_o curve is obtained[5]). We assume, therefore, that this is also true for AP. In fact, our 7.62 cm diameter curve appears to be linear in the range of 1.0 to 1.25 g/cc, and the 10.16 cm diameter curve of Ref. (1) appears to be linear in the range 0.6 to 1.25 g/cc.

In general, curves of D vs d are of an unsuitable form for extrapolation to the infinite diameter or ideal detonation velocity. Such a treatment is particularly inappropriate here because of the nonlinearity of the D vs ρ_o curves. Consequently we have followed the common practice of plotting D vs d^{-1} (a curve assumed linear if d is sufficiently large) and have neglected all smaller diameter data that appear low. In this treatment we have used no data on the high density side of the maximum on any curve. Such data obviously lead to too high values of the D vs d^{-1} intercept.

There is no theoretical guarantee that any of our D vs d^{-1} data are within the region of the usual linear relation or even that there will be a linear portion of the D vs d^{-1} curve. However, Evans et al[6] have shown that at ρ_o = 1.0 g/cc the D vs d^{-1} curve is linear over the diameter range of about 3.5 to 23 cm for an AP of 13 μ average size. Hence extrapolation at this density should give a good result. There is no comparable guidance at either 0.61 or 1.26 g/cc. At the lower density, our charges were of such poor quality that we accepted only two for shots. Here we have inadequate data for extrapolation. Although we have made a two-point estimate of D_i (ρ_o = 0.6), it is considered just that, an estimate not a determination. If a more finely ground sample of AP which produces better quality charges can be obtained, a determination of D_i will be attempted. (If uniform charges can be obtained at ρ_o = 0.6, they would be expected to give a linear

D vs d^{-1} curve over at least the same d range as the $\rho_o = 1.0$ g/cc data because AP seems to behave more ideally at lower densities.) In extrapolating the $\rho_o = 1.26$ g/cc data, one expects errors such as to make D_i too large, because the D vs ρ_o curves are already nonlinear at this density (see Fig. 9).

Table 3 contains the data used for the extrapolations (shown in Fig. 10) at densities of 0.61, 1.00, and 1.26 g/cc. In the latter two cases, a least squares fit to a straight line was used. Also shown in Fig. 10 are two points ($\rho_o = 1.25$ g/cc) read from the 6.35 cm and 10.16 cm curves of Ref. (1). The larger value falls on our curve; the lower, about 0.2 mm/μsec below our curve. However, the 6.35 cm data of Ref. (1) had a very large scatter; with smoothing that point too moves up to our curve as indicated by the arrow.

The D_i values from Fig. 10 are given in Table 3 and plotted as starred points in Fig. 9. Of these three values, D_i ($\rho_o = 1.0$ g/cc) is unquestionably the best. The charges were reproducible and the D vs d^{-1} data are linear over the experimental range of d. The point at $\rho_o = 1.0$ g/cc has consequently been heavily weighted in selecting the equation

$$D_i \text{ (mm/}\mu\text{sec)} = -0.016 + 3.784\,\rho_o, \qquad 0.6 \le \rho_o \le 1.26 \text{ g/cc} \quad (1)$$

which reproduces the values of Table 3 within ± 0.10 mm/μsec.

It is quite evident that Eq. (1) cannot hold at $\rho_o = 0$, for it would predict a negative (meaningless) velocity rather than one appropriate for a gaseous detonation. Perhaps the ideal curve bends sharply away from the linear relation at lower densities; there was a suggestion of this possibility in the HN data[5]. Moreover, the equations for linear segments between the three points are

TABLE 3

DETONATION DATA FOR EXTRAPOLATION TO IDEAL VALUES

Shot No.	d cm	d^{-1} cm^{-1}	D mm/μsec	$D = D_1 - bd^{-1}$: D_1 mm/μsec	$D = D_1 - bd^{-1}$: b/10 mm^2/μsec
			ρ_o = 0.61 g/cc		
149, 153	2.22	c	c		
101	2.54	0.394	1.69		
136	5.08	0.197	2.04		
				2.39	1.78
			ρ_o = 0.99 to 1.00 g/cc		
49, 55, 56	2.54	0.394	2.82		
60, 61	3.49	0.286	3.05		
53, 54	5.08	0.197	3.28		
63, 64	7.62	0.131	3.43		
				3.74	2.36
			ρ_o = 1.260 – 1.263 g/cc		
95	3.49	0.286	3.33[d]		
82, 83, 84[a]	3.81	0.262	3.42[d]		
70	5.08	0.197	3.85		
96[b]	6.35	0.158	4.08		
93	7.62	0.131	4.17		
				4.83	4.86

TABLE 3 (Cont'd)

Extrapolation of Smoothed D Data (Fig. 9) in D vs d^{-1} Form

ρ_o g/cc	D_1 mm/μsec	b/10 mm^2/μsec
0.8	3.08	2.18
1.15	4.26	3.03
1.30	5.02	5.76
1.35	5.27	6.82
1.40	5.50	8.18

[a] Respective values were 1.250, 1.256, and 1.264 g/cc and 3.415, 3.429, and 3.422 mm/μsec.

[b] Density was 1.265 g/cc; Shots 97 and 99 were at 1.294 and 1.280 g/cc and velocities were 4.110 and 4.089 mm/μsec.

[c] Failed at ρ_o = 0.60.

[d] Omitted from fit in Fig. 10.

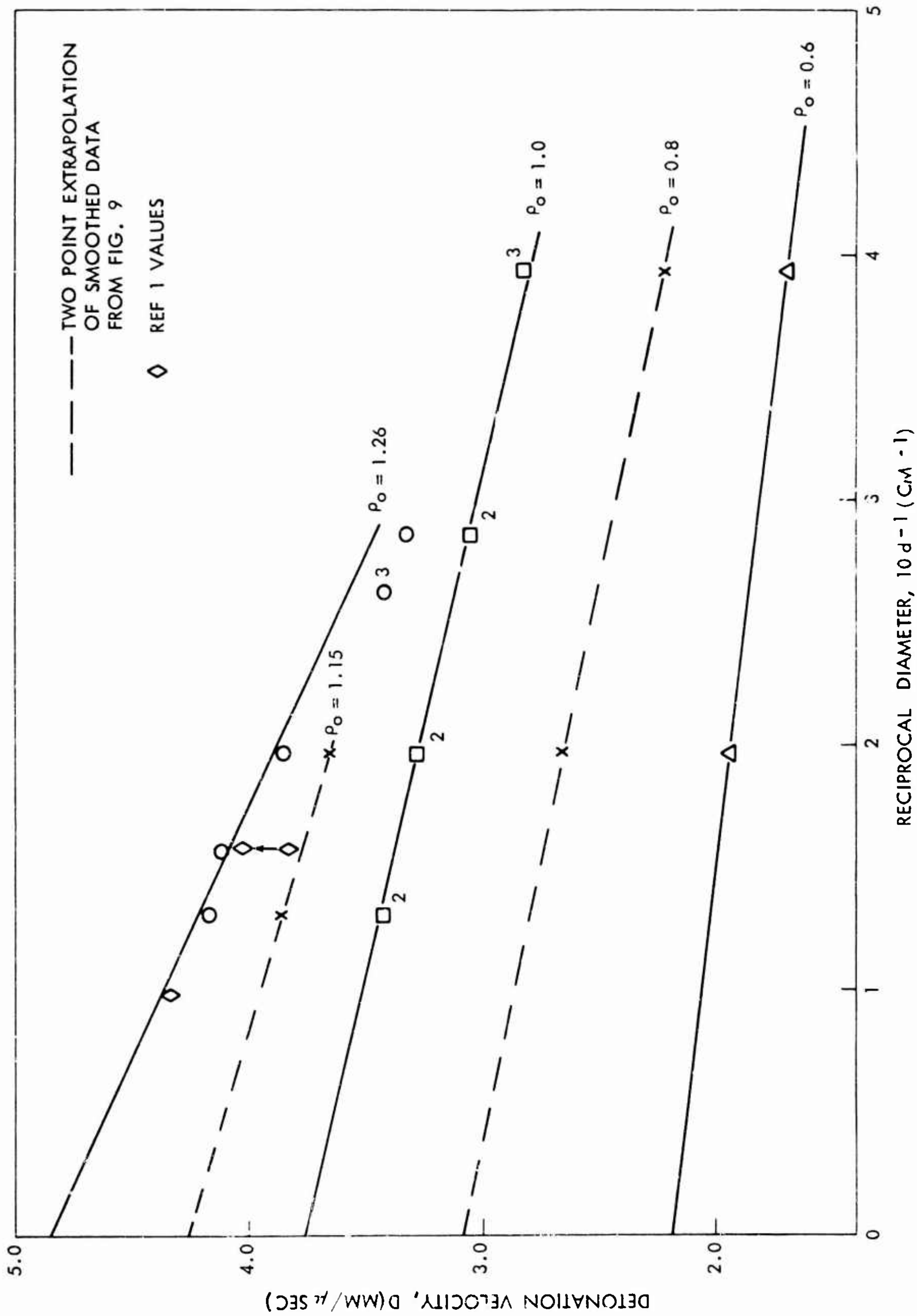

FIG. 10 EXTRAPOLATION TO IDEAL DETONATION VELOCITIES

$$D_i = -0.45 + 4.19\,\rho_o \qquad 1.0 \le \rho_o \le 1.26 \text{ g/cc}$$
$$D_i = 0.28 + 3.46\,\rho_o \qquad 0.6 \le \rho_o \le 1.0 \text{ g/cc} \tag{2}$$

and Eqs. (2) show the suggested concavity. (These equations can be used in place of Eq. (1) for interpolation between the data points.)

Eq. (1) as one bounding limit of Fig. 9 and the D_c vs ρ_c curve as the other limit give no indication of an intersection in the high density region. However, if the slope of the ideal curve is erroneously high, e.g., if the curve passed through the point at ρ_o = 1.0 g/cc with a much lower slope, it might intersect the somewhat concave D_c vs ρ_c curve at a density below the crystal density of 1.95 g/cc.

Comparison of Eq. (1) with results of other investigators does not resolve the uncertainties of the values at 0.6 and 1.26 g/cc. The comparison is shown in Table 4. Three sets of data agree very well at $\rho_o \sim$ 1.0 g/cc. The value at 1.24 g/cc agrees well with that obtained by extrapolating measurements made under confinement on a much coarser sample of AP, but exceeds by 8% the value given in Ref. (1). However, the curve of Ref. (1)

$$D_i = 1.012 + 2.688\,\rho_o \tag{3}$$

was not obtained by extrapolating D vs d^{-1}. Instead, it appears to be the D vs ρ_o data for the 10.16 cm charges. As Table 4 data show, when the Ref. (1) D vs d^{-1} data are extrapolated to $d^{-1} = 0$, they yield essentially the same D_i (ρ_o = 1.25 g/cc) value as Fig. 10 and as Ref. (7). Unfortunately, the fact that the same value can be obtained by the same treatment of three different sets of data still does not mean it is the correct one.

TABLE 4

COMPARISON OF IDEAL DETONATION VELOCITIES OF AP WITH THOSE REPORTED IN THE LITERATURE

ρ_o g/cc	D_1 (mm/µsec) Eq. (1)	10.2 cm curve of Ref. (1)	D vs d^{-1} Extrapolation, Ref. (1)	Other
0.61	(2.29 ± 0.10)	2.65 ± 0.10		
1.01	3.81 ± 0.10*	3.73 ± 0.10		3.75 ± 0.15[6]
1.24	4.68 ± 0.10	4.34 ± 0.10		4.64[7]***
1.25	4.73 ± 0.10	4.37 ± 0.10	4.85 ± 0.1**	

*By interpolation with Eq. (2), value is 3.78 mm/µsec.

**One point smoothed as in Fig. 10; otherwise value obtained is even higher.

***This value obtained by a two-point D vs d^{-1} extrapolation of velocities measured on confined AP of 55 - 60 µ particle size.

There is no similar way to reconcile the difference between our estimate of D_1 (ρ_o = 0.6) and the value of Ref. (1). Eq. (3) is certainly preferable to Eq. (1) in that it is more physically reasonable at low densities. Yet we hesitate to adopt the 0.6 g/cc value when six shots at 6.35 cm diameter showed a range of 2.38 to 2.71 mm/µsec. Nevertheless, the Ref. (1) value may be the better, and there is some support for it given in the Appendix.

We hope to check both the high and the low density values with finer samples of AP. The smaller particle size may permit the production of better quality low density charges. It may also increase the detonation velocity so that several linear D vs ρ_o curves can be obtained (linear at and beyond ρ_o = 1.26) at diameters at or below d = 7.62 cm, the permissible limit in NOL bombproofs.

Theoretical computations of the detonation characteristics of AP have been carried out by two different groups[1,4], but these do not resolve the problems either. Different equations of state were used, and the results obtained do not agree with each other. This is illustrated in Fig. 11 which shows the disagreement between the two computed D_1 vs ρ_o curves as well as between both theoretical curves and the experimentally derived values of this report. Chaiken[8] has given a detailed discussion of the inadequacy of the Ruby computed values to reproduce the AP behavior.

In summary, Eq. (1) is the best representation of the present data as a linear segment of the D_1 vs ρ_o curve. The crosses plotted about it in Fig. 9 were obtained from the smoothed finite diameter curves at loading densities of 0.80, 1.15 and 1.30 g/cc. In each case a two point extrapolation of D vs d^{-1} gave a value on the ideal curve within ± 0.10 mm/µsec.

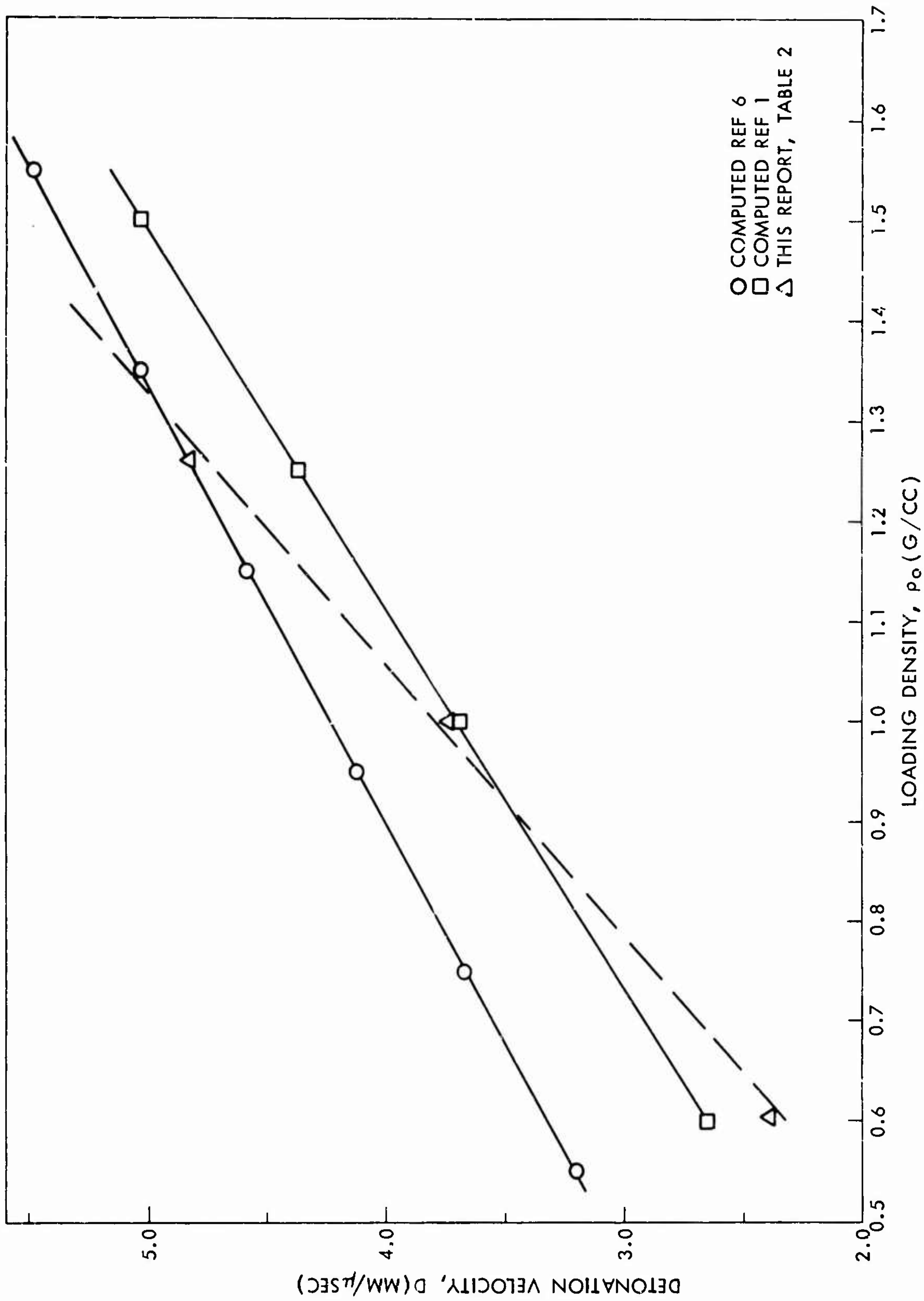

FIG. 11 COMPARISON OF COMPUTED AND MEASURED DETONATION VELOCITIES

Effect of Porosity on Reaction Zone Length

The detonability limit curve of Fig. 6 has already shown that for this AP, the reaction zone length increases with increasing ρ_o in the range $\rho_o \geq 1$ g/cc. Anderson and Pesante[1] showed that their $D = D(\rho_o, d)$ data were described reasonably well by any of the available diameter theories, but the scatter of their data was much larger than ours. In particular, our best data (those at 1.0 g/cc) show a linear D vs d^{-1} curve and a non-linear D^{-2} vs d^{-2} curve. Hence the Eyring curved front theory[9] fits our data better than the Jones nozzle theory. Consequently, we shall use the curved front theory to compute nominal reaction zone lengths.

For unconfined charges, this theory gives

$$\frac{D}{D_i} = 1 - \frac{a}{d} \qquad (4)$$

where a is the reaction zone length.

The curves of Fig. 11 are in the form

$$D = D_i + bd^{-1}$$

Hence

$$\frac{D}{D_i} = 1 + \frac{b}{D_i}\, d^{-1}$$

and

$$a = -b/D_i \qquad (5)$$

Values of b and D_i are given in Table 3. From them, nominal reaction zone lengths have been calculated from Eq. (5) and are listed in Table 5. They indicate a decrease in the reaction zone length (a) as

TABLE 5

NOMINAL REACTION ZONE LENGTH AS FUNCTION OF LOADING DENSITY FOR AP

Loading Density ρ_o, g/cc	Nominal Reaction Zone Length* mm
0.6	7.5
(0.8)	(7.1)
1.0	6.3
(1.15)	(7.1)
1.26	10.0
(1.30)	(11.5)

*Curved Front Theory

Values in parentheses from interpolations and extrapolations the loading density increases from 0.6 to 1.0 g/cc and an <u>increase</u> as ρ_o increases above 1.0 g/cc. This is consistent with the form of the suggested limit curve of Fig. 8.

The AP trend, reaction zone length vs porosity, for $\rho_o = 0.6$ to 1.0 g/cc is qualitatively the same as that of conventional H.E. Moreover, the reaction zone lengths in this region are about the same size as those of common H.E. For example, a TNT at 48% TMD had b and D_1 values of $-20.3\ mm^2/\mu sec$ and $4.85\ mm/\mu sec$, respectively[10]. Its computed nominal reaction zone length is 4.2 mm whereas at the same porosity AP has $\rho_o = 0.94$ g/cc and, by interpolation (Table 5), a zone length of 6.5 mm.

The reaction time (τ) is related to the reaction zone length by

$$\tau = (\bar{\rho}/\rho_o\ D)\ a \tag{6}$$

where $\bar{\rho}$ is the average density between the von Neumann and the C - J planes. Andersen and Pesante[1] believe that the detonation of granular AP is a grain burning process in which the rate-controlling step is a sublimation. In this case

$$\tau = \bar{R}_g/B \tag{7}$$

where $\bar{R}_g$ is the average radius of the explosive particles and B is a linear thermal surface vaporization rate. By a linear pyrolysis technique, they determined for AP

$$B\ (cm/sec) = 5.88\ T_s \exp\ (-20{,}000/RT_s)^* \tag{8}$$

*Changed in subsequent work to 31 T_s exp $(-22{,}000/RT_s)$ and then to 21 T_s exp $(-21{,}500/RT_s)$. Units of the exponent are cal/mole.

In order to use Eq. (8) to compute τ and hence a, it is necessary to know the detonation temperature T_j and assume that it is the particle surface temperature T_s. Andersen and Pesante did this for their computed T_j and got τ values comparable to those given by the diameter effect theories. However, this involved extrapolation of their pyrolysis data to the computed detonation temperatures. Of all detonation properties, T_j is least well known. For example, Ref. (1) shows T_j of 1915°K to 2075°K computed for ρ_o of 0.6 to 1.5 g/cc whereas Ref. (6) gives 1722°K to 1039°K for ρ_o of 0.55 to 1.55 g/cc. There seems little point of further application of Eq. (8) to unknown T_j.

Although we have followed conventional methods in the treatment of the present data, it is not at all clear how applicable the usual hydrodynamic treatments are at the very low densities of some granular charges. The present results suggest that different mechanisms of reaction may be dominant in the detonation of AP at low and at high densities. One factor which might affect initiation and propagation at low densities (and be lessened or absent at high densities) is the flow of hot gas products into the unreacted explosive ahead of the propagating detonation front. An attempt will be made to record such a disturbance if it exists in the very porous charges.

SUMMARY

The family of curves $D = D(\rho_o, d)$ obtained for AP (10 μ) shows systematic and regular variations. The behavior pattern differs from that of conventional H.E. such as TNT in that

(1) D is not a linear function of ρ_o at a given d (In fact, D is not uniquely defined by ρ_o and d since the same velocity can be exhibited at two density values.)

(2) The critical or failure density increases with increasing diameter in the range of TMD > 50%.

(3) Failing reactions persist and propagate as far as 3 - 4 diameters and more under conditions that are subcritical.

(4) Behavior appears more ideal at low densities than at high.

In addition to the above trends found in the range of TMD > 50%, we also found some evidence that at very low densities (TMD ~ 30 to 50%) AP (10 μ) exhibits a detonability limit behavior qualitatively similar to that of TNT at the same high porosity.

ACKNOWLEDGMENT

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APPENDIX A

SUPPLEMENTARY DATA

Table A1 contains experimental details for the optical conditions for each record: flasher, film, charge length viewed and writing speed of the camera.

AP XP-11 was originally very similar to XP-17, but its plastic container was torn and the AP picked up enough moisture to cake. The cake was dried and rolled to obtain enough material to make low density charges of different diameters. The first set of charges were so poor that heterogeneous portions could be observed on the stills taken with each shot. These data are considered worthless and will not be reported. The second series was of much better quality, though still far from satisfactory. Their results are given in Table A2 and plotted D vs d^{-1} in Fig. A1. The Ref. (1) D_i value from the 10.2 cm curve and the present value from Eq. (1) are also given in Table A2 for comparison. The present value checks the Ref. (1) value rather than that of Eq. (1). However, the charges were still unsatisfactory and the D vs d^{-1} slope or b value of Table A2 indicates a very coarse charge (compare with b values of Table 3) or possibly a higher density than 0.7 g/cc with a collapse of the charge before detonation occurred. Consequently, a new lot of finely ground AP must be procured in order to check this low density point.

TABLE A1

EXPERIMENTAL CONDITIONS FOR THE SHOTS

Shot No.	Flasher a	Film b	Length Observed ir	Writing Speed W mm/µsec
137			7.5	1
147			7.5	2
173			7.5	2
174			7.5	2
153			7.5	1
149			2.5	1
141			7.5	1
143			2.5	1
144			2.5	2
142			7.5	1
148			2.5	2
52		P	7.5	1
101			7.5	1
150			2.5	2
124			2.5	2
49		P	7.5	1
55		P	7.5	1
56		P	7.5	1
127	M		2.5	3
126	M		7.5	1
139	M		7.5	1
85	M	P	7.5	1
60		P	7.5	1
61		P	7.5	1
131	M		2.5	3

TABLE A1 (Cont'd)

Shot No.	Flasher a	Film b	Length Observed in.	Writing Speed W mm/μsec
132	M		2.5	3
89	N	P	7.5	1
87	N	P	7.5	1
88	N	P	7.5	1
94	N	P	7.5	1
95	N	P	7.5	1
98	M	P	2.5	3
109	N	P	7.5	1
111	M	P	2.5	3
110	M	P	2.5	3
112		P	7.5	2
136	M over A		7.5	1
154	M over A		2.5	3
53		P	7.5	1
54		P	7.5	1
70	M	P	7.5	1
71	M	P	7.5	1
72	M	P	7.5	1
73	M	P	7.5	1
74	M	P	7.5	1
69	M	P	7.5	1
63		P	7.5	1
64		P	7.5	1
91	N	P	7.5	1
92	N	P	7.5	1
93	N	P	7.5	1
114	M	P	2.5	3

TABLE A1 (Cont'd)

Shot No.	Flasher a	Film b	Length Observed in.	Writing Speed W mm/μsec
116		P	2.5	3
113	M	P	2.5	3
115	M	P	2.5	3
134	M		7.5	2
117	M	P	7.5	1
118		P	7.5	3
82	S	P	7.5	1
83	S	P	7.5	1
84	S	P	7.5	1
96	N	P	7.5	1
97	?	P	7.5	1
99	N	P	2.5	3
369			2.5	2
370			2.5	2
371			2.5	2
376			2.5	2

a. Cellulose acetate used unless otherwise specified. Symbols are: A cellulose acetate; M magic tape; N none; S Scotch tape.

b. T Tri-X film used unless P (Panatomic-X) specified.

TABLE A2

DATA FOR CHARGES PREPARED FROM XP-11 AFTER CAKING

Shot No.	Diam. d cm	d^{-1} cm^{-1}	ρ_o g/cc	D mm/µsec	D_i mm/µsec	$10^{-1}b$ $mm^2/\mu sec$
369	3.49	0.286	0.723	1.889		
370	5.08	0.197	0.723	2.245		
371	6.35	0.158	0.721	2.462		
376	7.62	0.131	0.722	2.486		
					3.00	3.84
					2.95*	
					2.71**	

*Eq. (3), 10.2 cm curve from Ref. (1)
**Eq. (1)

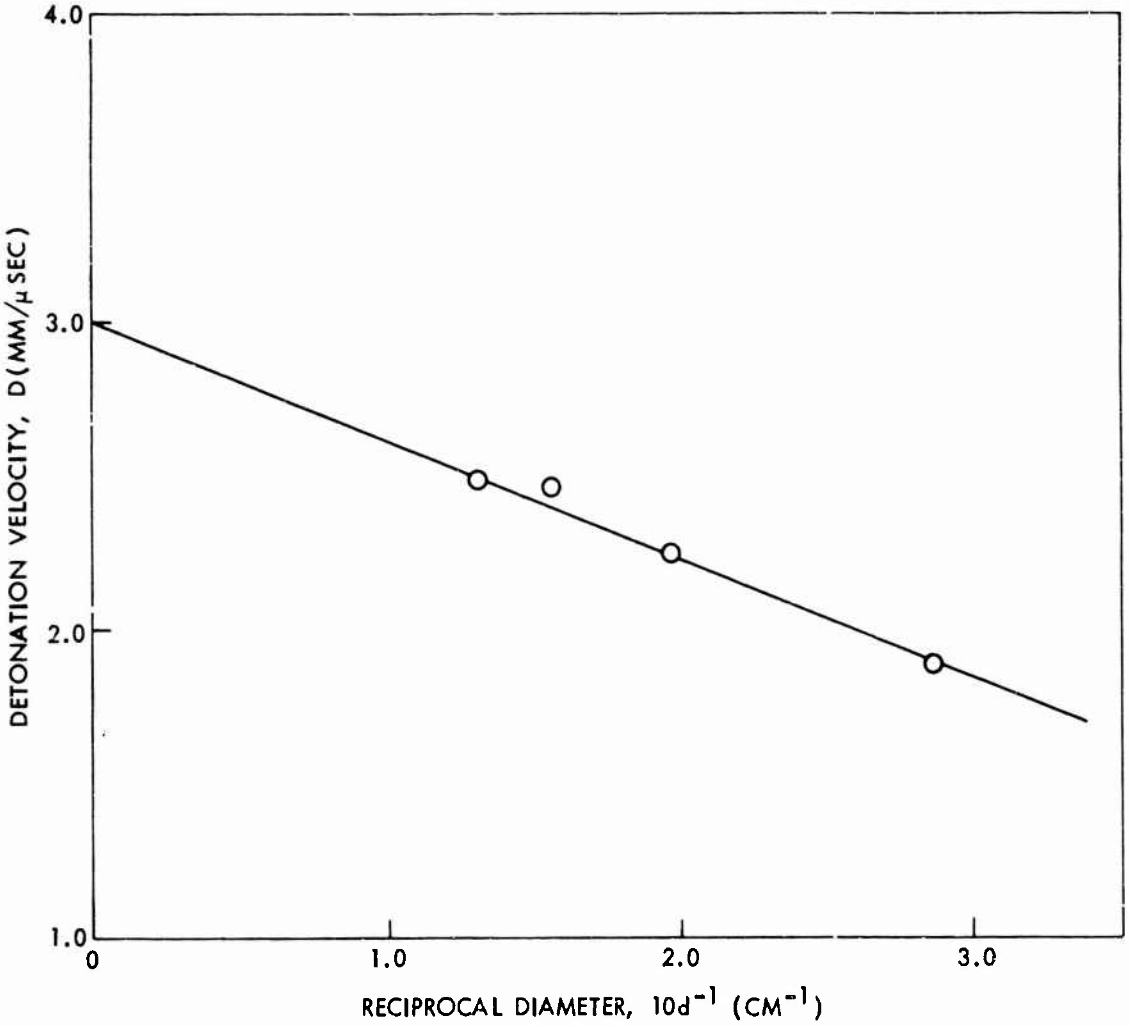

FIG. A1 EXTRAPOLATION TO D_i AT ρ_0 = 0.72 G/CC FOR AP XP-11(CAKED)

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 67-71)
THE DETONATION BEHAVIOR OF AMMONIUM PERCHLORATE AS A FUNCTION OF CHARGE DENSITY AND DIAMETER, by A. R. Clairmont, Jr. and others. 20 June 1967. 43p. charts, tables. NOSC task 033 102 F009 06 01.

UNCLASSIFIED

The detonability limits and detonation behavior were studied for a finely ground ammonium perchlorate (AP). The typical finite diameter D vs ρ_o curve is non-linear and exhibits a maximum in detonation velocity. The failure curve d_c (diameter) vs ρ_c (critical density) shows a monotonic increase in d_c with ρ_c in the range $\rho_o < 1.0$ g/cc and is opposite in trend to that for TNT.

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2. Detonation - Velocity
3. Ammonium perchlorate
I. Title
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III. Project

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13. ABSTRACT

The detonability limits and detonation behavior were studied for a finely ground ammonium perchlorate (AP). The typical finite diameter D vs ρ_0 curve is non-linear and exhibits a maximum in detonation velocity. The failure curve d_c (diameter) vs ρ_c (critical density) shows a monotonic increase in d_c with ρ_c in the range $\rho_0 \geq$ 1.0 g/cc and is opposite in trend to that for TNT.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Nitroguanidine						
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Detonation velocity						
Low velocity detonation						
Detonability						
Critical diameter						
Critical density						

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This publication is changed as follows:

Delete list of key words on DD Form 1473 (page 2) and the library abstract card and add the following words:

Ammonium perchlorate
Detonation velocity
Detonability
Shock sensitivity
Critical diameter
Critical density

Insert this change sheet between the cover and the title page of your copy. Write on cover "Change inserted"

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